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Nonlinear Dynamics in Spin-Torque-Induced Magnetization Oscillation Phenomena(Digest_要約)

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Abstract

Under a dc electric current, a multilayered magnetic nanostructure can emit microwaves that originate from self-sustained magnetization oscillations driven by spin-transfer torque. The first direct observation of the spin-torque-induced magnetization oscillation phenomenon was reported in 2003, and this type of nanoscale structure is referred to as a spin-torque nano-oscillator (STNO). This thesis presents investigations into dynamical properties of STNOs by theoretical and computational approaches and experimental analysis.

The study of this novel oscillator is part of the field of spintronics. One advantage of STNOs is that oscillation frequencies are easily tunable by dc current and magnetic field. Over the last decade, these systems have attracted much attention from the perspective of technological applications, such as tunable microwave generators in wireless communications and next-generation magnetic heads in magnetic hard-disk drive (HDD) technology. The main issues to be addressed for these applications are how to enhance the output power, how to tune the oscillation frequency, and how to elicit the oscillation stability. Finding a solution to the third issue, how to obtain stable oscillations, is of the utmost importance, and a deep understanding of the magnetization dynamics in STNOs is essential for it.

The main objective of this thesis is to discover how to control the magnetization dynamics of STNOs for obtaining stable oscillations. For the purpose, we investigate dynamical properties of STNOs by employing the concepts and methods developed in the field of nonlinear sciences. This thesis focuses on the following four aspects of STNOs: (1) influence of interlayer couplings on magnetization dynamics, (2) distinct features of STNOs in comparison with other oscillators, (3) conditions for a spatially uniform magnetization oscillation, and (4) responses of STNOs to external stimuli.

On subject (1), we examine a coupled magnetic system in which plural magnetic layers dynamically interact with each other via spin-torque or/and dipolar couplings. Such a coupled system has more dynamical degrees of freedom than a standard STNO with a single dynamic magnetic layer, and thus, by examining it, we can aim at further understanding of possible magnetization motions in STNOs and finding some new stable oscillation modes. In particular, we address the subject (1) from the aspect of the

synchronization of magnetizations that is expected to occur in such a coupled system. By performing numerical simulations of the Landau–Lifshitz–Gilbert–Slonczewski (LLGS) equations, we show that synchronized oscillations of a pair of magnetizations occur depending on magnetic field and current.

On subject (2), we define the novel oscillator, STNO, in a variety of other oscillators by employing a general concept of limit-cycle oscillations. By applying the reductive perturbation method to the LLGS equation, we derive the Stuart–Landau equation, which is known to describe the simplest limit-cycle oscillator, and develop a noisy oscillator model for STNOs. In the developed oscillator model, the characteristic property of STNOs is represented by the amplitude–phase coupling (APC) factor δ , and the distinct feature of STNOs is that they have a wide range of the APC factor ($|\delta| \sim 0\text{--}50$) sensitively depending on magnetic fields. Moreover, the model predicts that the smaller AP coupling leads to the higher oscillation stability. For verifying the prediction, we also conduct an experiment to extract the APC factor. By measuring the power spectrum density of microwave signals from a MgO–based STNO and analyzing the spectrum linewidth against inverse output power plot, we obtain small APC factor ($|\delta| \sim 3$) for stable oscillations with a narrow spectrum linewidth ($\Delta f \sim 10$ MHz).

On subject (3), we investigate a condition of spatially uniform oscillations, which are expected to turn into highly coherent microwave emissions with a distinct frequency and a narrow linewidth. We first derive the complex Ginzburg–Landau equation (CGLE) for STNOs, and then elucidate a key factor that determines spatiotemporal magnetization–oscillation patterns by employing the general theories based on the CGLE. Considering the Benjamin–Feir criterion for STNOs, we show that a uniform oscillation can be established when the nonlinear shift of frequency is positive and exemplify that for an elliptical nanopillar device, the nonlinear frequency shift can be positive when an in-plane bias field is applied in the short axis of the ellipse. We also describe that the establishment of uniform oscillations is significantly affected by the cooperation of the exchange spin-wave dispersion and nonlinear shift of frequency.

Subject (4) is addressed from a practical point of view. Evaluation of quick responsiveness of STNOs is essential for examining the application possibility of them to some high-speed functional devices. We verify that the frequency of the oscillating magnetization in an STNO is able to change promptly in response to magnetic pulses with little delay while maintaining a stable oscillation. This dynamical property indicates that information about magnetic pulses can be retrieved by detecting the frequency variation of an STNO, implying that the recently proposed novel magnetic sensor consisting of an STNO, “STO Reader”, is feasible as a next-generation HDD read head.

The fundamental operation of the novel sensor is also demonstrated through numerical computations.